Convergence of Broadband Optical and Wireless Access Networks

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ABSTRACT

This paper describes convergence of optical and wireless access networks for delivering high-bandwidth integrated services over optical fiber and air links. Several key system technologies are proposed and experimentally demonstrated. We report here, for the first ever, a campus-wide field trial demonstration of radio-over-fiber (RoF) system transmitting uncompressed standard-definition (SD) high-definition (HD) real-time video contents, carried by 2.4-GHz radio and 60-GHz millimeter-wave signals, respectively, over 2.5-km standard single mode fiber (SMF-28) through the campus fiber network at Georgia Institute of Technology (GT). In addition, subsystem technologies of Base Station and wireless tranceivers operated at 60 GHz for real-time video distribution have been developed and tested.

Keywords: Optical-wireless, radio-over-fiber, millimeter-wave

1. INTRODUCTION

With the high-speed broadband penetration, Internet traffic among residential and business customers has placed a huge bandwidth demand on the underlying telecommunications infrastructure [1]. Today's Internet traffic patterns have been propelled from voice- and text-based services to user-generated interactive video services. Peer-to-peer (P2P) traffic, as the largest share of current internet traffic, contains almost 70% traffic related to the exchange of both static video files and real-time video communications with dynamic video contents [2]. At the same time, irresistible bandwidth requirements for delivering multi-channel high-definition television (HDTV) signals and online gaming services will keep growing toward multigigabits/second in the near future. In response to this remarkable development, the metro and core networks of the telecommunication infrastructure have experienced tremendous growth in bandwidth and capacity with the wide deployment of fiber-optic technology in the past decade [3][4]. As shown in Fig. 1, data speeds in metro and long-haul systems are evolving from 10-Gbps to 40-Gbps transmission, 100 Gbps per wavelength channel system is taking shape as next step for core and metro networks [4].
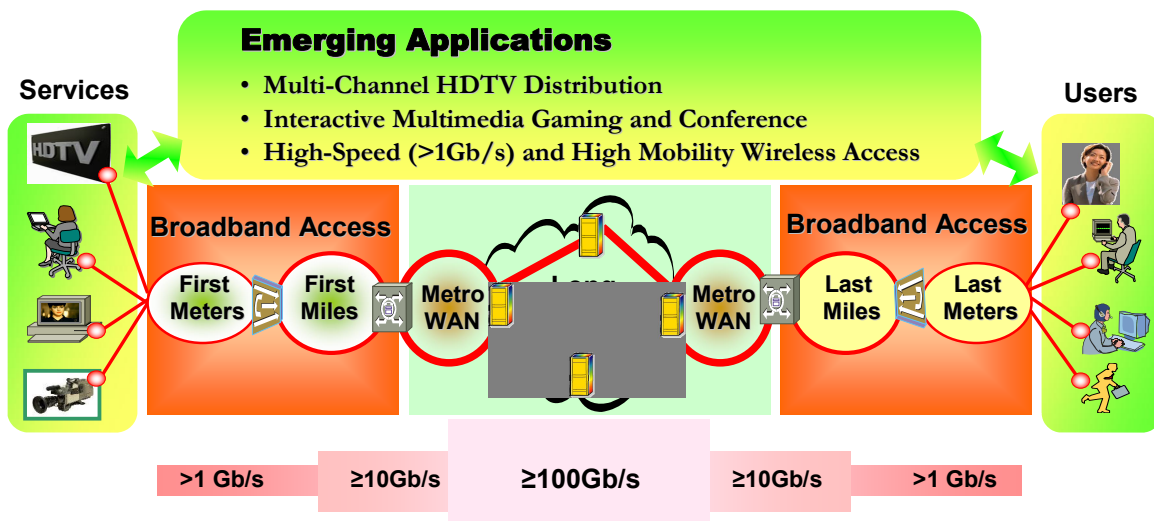

Fig. 1 Emerging broadband applications and future network requirements.

However, the ultimate bottleneck to the end users is still contributed by the last mile and last meters wireline and wireless access systems with limited bandwidth capacity. In order to avoid being such bottleneck in the last miles and last meters, and to exploit the benefits of both wired and wireless technologies, carriers and service providers are actively seeking a converged network architecture to deliver various services to serve both fixed and mobile users. Therefore, optical-wireless access technologies, named as radio-over-fiber (RoF), have been considered the most practical and efficient solution to increase the capacity, coverage, bandwidth, and mobility, and is especially suitable for providing flexible and full connectivity for in-building environments such as conference centers, airports, hotels, shopping malls - and ultimately to homes and small offices [5][6]. We have designed several enabling technologies required for super-broadband wireless services delivery over optical fibers and air links in symmetric optical-wireless access networks [7][8]. In this paper, we further propose some key technologies to significantly increase the dispersion tolerance for up-converted optical millimeter-wave signals, including photonic frequency tripling (PFT) technology, remote signal regeneration and upconversion for extended passive optical networks (PONs), and orthogonal frequency division multiplexing (OFDM) optical systems. In addition, for the first time a campus-wide field trial demonstration for the delivery of uncompressed 270-Mb/s standard-definition television (SDTV) and 1.485-Gb/s HDTV video signals between on-campus buildings over 2.5-km fiber network at Georgia Institute of Technology is proposed.

2. LONG-REACH TRANSMISSION WITHOUT DISPERSION COMPENSATION

At millimeter-wave frequencies especially for 60-GHz band, the transmission distance of optical-wireless links is severely limited by power fading and time-shifting arising from chromatic dispersion in the fiber. Such short-reach access system will lead to higher cost and inflexibility in terms of network deployment and management [9]. In this section, three schemes are reported to simultaneously extend the fiber transmission distance for millimeter-wave optical-wireless signals.

2.1 Dispersion-tolerant transmission based on PFT technology

Simultaneous multi-band modulation has been demonstrated for flexible configuration in hybrid fiber-fed wireless systems. However, no work has been undertaken for multi-band generation using a dispersion-tolerant scheme within the 60-GHz millimeter-wave band with low-frequency components. The designed schematic diagram for millimeter-wave, microwave, and baseband signal generation and dispersion-tolerant transmission is shown in Fig. 2. Wireless baseband signals initially modulate an RF signal at 20 GHz (one third of the LO frequency). The resulting signal is then subcarrier multiplexed (SCM) onto the optical carrier using an intensity modulator, thus forming dual sidebands. An optical filter with a sharp passband window is used for vestigial sideband (VSB) filtering. The filtered signals are then injected into a dual-arm Mach-Zehnder modulator (MZM) to perform the optical carrier suppression (OCS) using the same clock. After OCS, the optical carrier and the remaining sideband have been suppressed, leaving four longitudinal subcarriers, equally-spaced by 20 GHz, two of which carry the signal. After transmission, another interleaver is used to separate different frequency bands that are needed for wired and wireless connections.
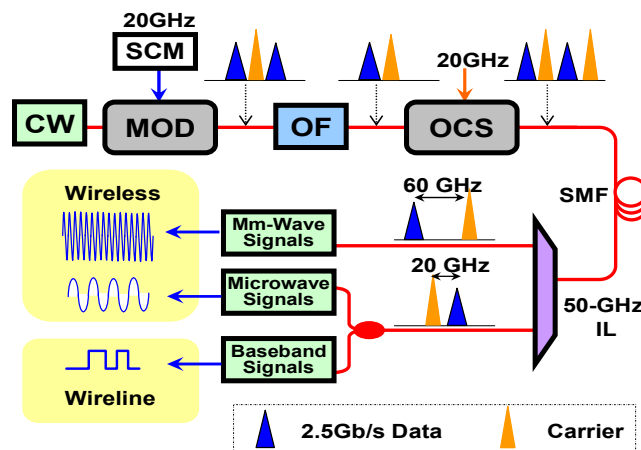

Fig. 2 Schematic diagram of PFT scheme, OF: optical filter.

Figure 3 depicts the experimental setup of the simultaneous multi-band generation and dispersion-tolerant transmission based on PFT technology. At the central office (CO), a continuous wave (CW) lightwave is generated by a tunable laser (TL) and is modulated by a LiNbO3 MZM. The 21-GHz sinusoidal wave is generated using a frequency doubler (FD). This is then mixed with 2.1-Gb/s pseudo-random binary sequence (PRBS) data to drive the modulator. The VSB filtering is achieved by cascading a 25/50- and a 50/100- GHz optical interleaver with 100-GHz periodicity. A dual-arm MZM biased at $V\pi$ and driven by two complementary 21-GHz clocks follows to suppress the two injected carriers while generating four subcarriers with alternate modulation. After transmission over 50-km of SMF-28, the other 50/100-GHz optical de-interleaver is then used to separate the four subcarriers. Direct heterodyne detection of the 63-GHz wireless is achieved by a 60-GHz bandwidth PIN photodiode. The converted electrical mm-wave signal is then amplified by an electrical amplifier (EA) and down-converted to its baseband form. Two central subcarriers, including both microwave and wired signals, are directly detected by a 2.5-Gbps receiver with 3R function for the wired baseband connection. The optical spectra of the 21-GHz microwave and 63-GHz millimeter-wave signals are also shown in Fig. 3 insets. The power penalty after 50-km fiber transmission for both signals is less than 1.0 dB at the given BER of 10^{-9}. This technology has unique advantages in terms of low-bandwidth requirements for both optical and electrical components to realize dispersion-tolerant transmission for 60-GHz ROF systems.
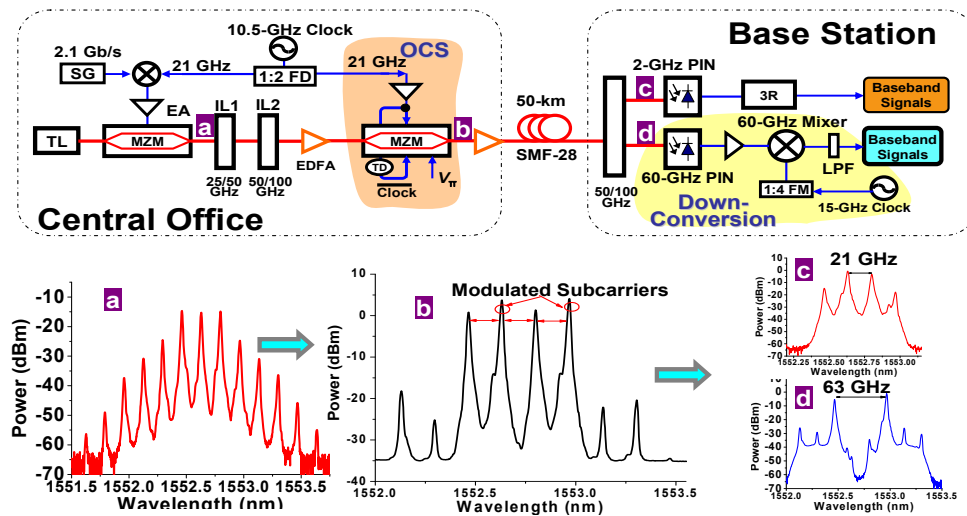

Fig. 3 Experimental setup (TL: tunable laser, TD: time delay, FD: frequency doubler, IL: optical interleaver).

2.2 Remote optical upconversion for long-reach PON

To extend the reach of millimeter-wave wireless signals over PONs while simultaneously achieving cost reduction of all hybrid optical network units (ONUs), a long-reach hybrid PON architecture is designed and experimentally demonstrated for delivering multi-gigabit wired and wireless services to 128 ONUs using remote signal regeneration and upconversion techniques [10]. Fig. 4 illustrates the conceptual diagram of proposed long-reach and conventional short-reach 60 GHz millimeter-wave hybrid optical-wireless access networks. Unlike the short-reach access sending upconverted millimeter-wave signals at single λS from an optical line terminal (OLTs) in the CO, the basic idea behind the proposed long-reach scheme is to deliver 2.5-Gb/s baseband signal and 60-GHz millimeter-wave carrier independently at different wavelength λ_{L1} and λ_{L2} from OLT_L and then mix them at the LE with a low-cost remote optical upconverter, which is commonly utilized as an extended and managed network stage in optical access network. Thus, before arriving at the LE headend, both uncorrelated lightwaves can suffer from the least dispersion-induced penalties over long-distance fiber transmission. After the LE, the output 60-GHz millimeter-wave at λ_{L2} will carry 2.5-Gb/s data and then be delivered through RN to hybrid ONUs or legacy ONUs for wireless and wired access. In addition, the structure as well as the expense of these hybrid ONUs can be further simplified and reduced by shifting their local upconversion functionality toward the LE. Fig. 5 shows the experimental setup for the long-reach 60-GHz millimeter-
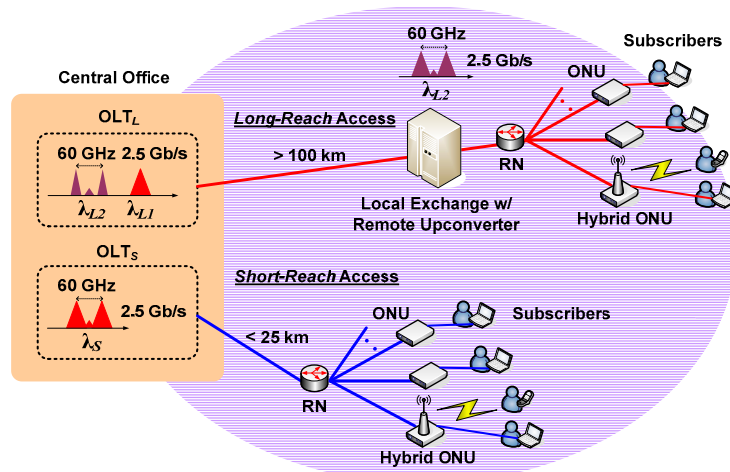
Fig. 4 Network architecture of the long-reach and conventional short-reach hybrid optical-wireless access networks.

wave hybrid optical-wireless access network employing remote optical upconverter at the LE. After transmitted over 100-km standard single mode fiber (SSMF), two lightwaves are fed into an LE for remote signal regeneration and upconversion. The LE consists of two optical circulators (OCs) and three in-line EDFAs for bidirectional amplification, and a remote optical upconverter module, which consists of a thin-film filter (TFF), a 2.5-Gb/s optical receiver (Rx) and a 2.5-GHz intensity modulator (IM). After fed into the TFF with low insert loss of 0.5 dB, two lightwave channels are separated; the 60 GHz optical millimeter-wave signals pass through the IM, while the 2.5-Gb/s baseband signal is detected and regenerated by an optical receiver, and then to drive the IM directly to realize remote all-optical upconversion. The proposed remote optical upconverter is cost-effective since only low-frequency devices are sufficient to handle with 60 GHz signal upconversion. After transmission of another 25-km SSMF, 2.5-Gb/s data on 60-GHz optical millimeter-wave are received for wired and wireless applications. The waveforms and optical eye diagrams are also shown in Fig. 5 insets (a)-(f) for comparison. Time division multiple access (TMDA) is one of the practical upstream solutions, which should be well defined at the MAC layer for optical-wireless networks in the near future.
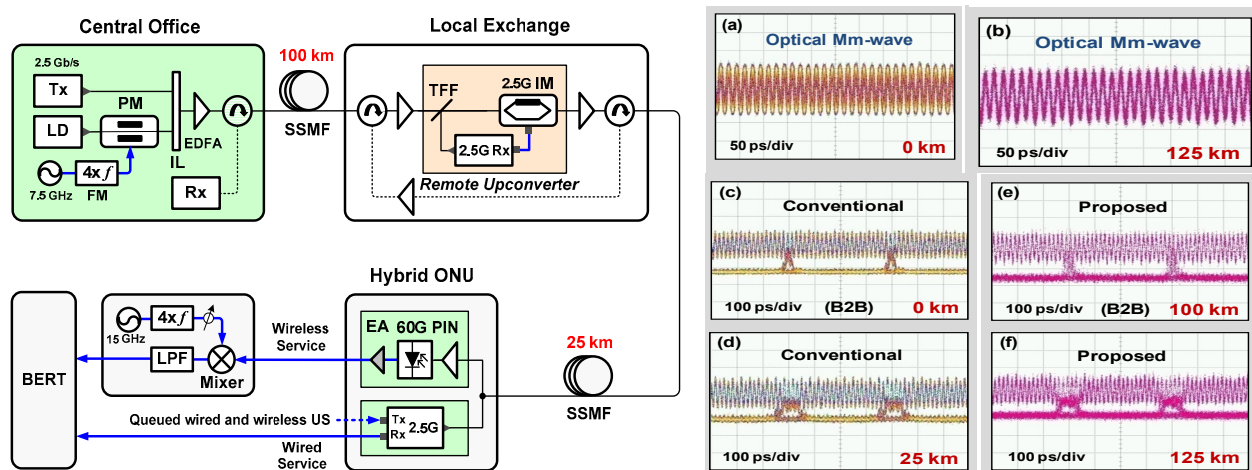

Fig. 5 Experimental setup and measured waveforms and eye diagrams.

Remote optical up-conversion without LO signal delivery from the CO to the LE is another way to realize the extended reach. In this way, the optical LO signal will not experience any distortion before optical mixing. The proposed long-reach architecture for the integration of wavelength division multiplexed (WDM) PON with 60-GHz optical wireless

system is shown in Fig. 6. It is noted that both OCS modulation and phase modulation can be used to remote optical 60-GHz millimeter-wave generation and upconversion. The power penalties at the given BER of 10^{-9} after 125-km transmission are about 0.5 dB and 1.4 dB for wired and wireless data, respectively.
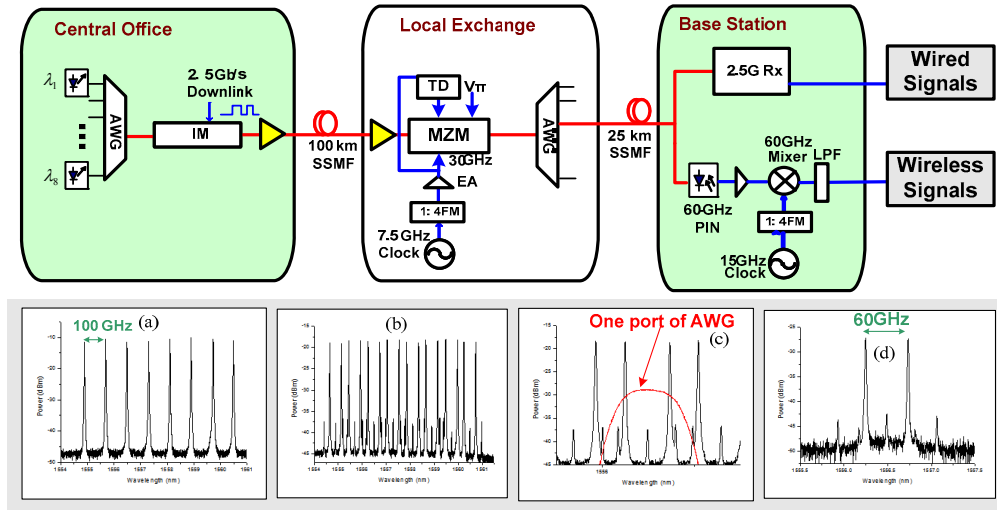

Fig. 6 Experimental setup and optical spectra of remote upconversion without optical LO delivery.

2.3 OFDM modulation format for long-reach optical-wireless signals transmission

OFDM has widespread use in wireless LANs, broadband access networks and in digital broadcasting. Recently, optical transmission systems employing OFDM have gained considerable research interest because OFDM can combat fiber chromatic dispersion and has the capability to use higher level modulation formats to increase spectral efficiency. Therefore, the combination of OFDM and optical-wireless systems is naturally suitable for optical-wireless systems to extend the transmission distance over both fiber and air links [11][12]. Optical phase modulation and the subsequent optical filtering are used to generate and up-convert optical millimeter-wave signals. Figure 7 depicts the experimental setup of the 40-GHz OFDM optical-wireless system. The 1-Gb/s OFDM baseband signals are generated offline with Matlab program. The 1-Gb/s OFDM signals are mixed with a 20-GHz sinusoidal wave to realize SCM for the millimeter-wave signals and then used to drive the MZM.
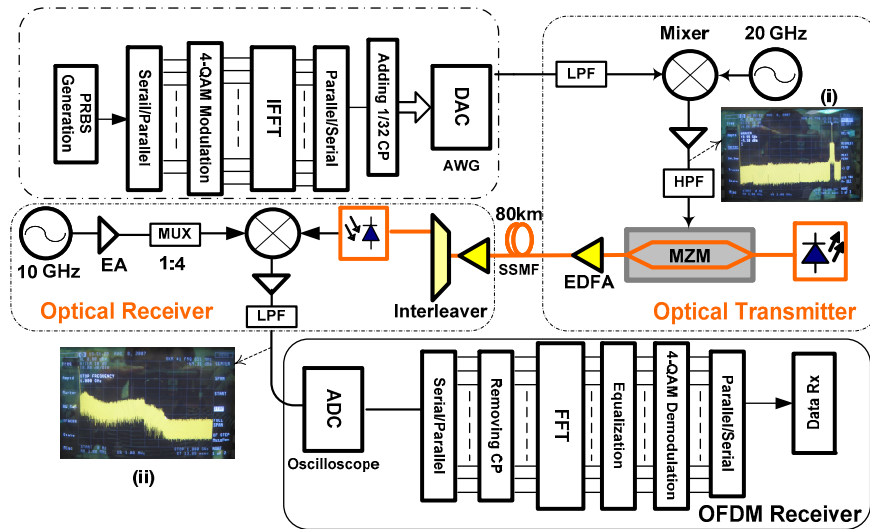

Fig. 7 Experimental setup of OFDM optical-wireless system at 40-GHz millimeter-wave carrier.

The down-converted signals are sampled with a real-time digital oscilloscope (Tektronix TDS6154C) at 1.25 GSample/s. The received data are processed and recovered offline with a Matlab program as an OFDM receiver. The electrical spectrum of down-converted OFDM signals is shown in Fig. 7 inset (ii). The spectrum fluctuations for different frequency components arise from the nonlinear response of TL, MZM, and optical amplifier because of the large optical power. Figure 8 shows the BER curves of the B-t-B and 80-km SSMF transmission as a function of the received optical power. 1.17e6 cumulative bits are evaluated for both tests. Compared with the B-t-B case, it has less than 0.5-dB power penalty at the BER of 10^{-6}. The inset shows the constellation of the OFDM signals at the received power of -25 dBm. We also measured 16-QAM signals on 40 GHz carrier. The constellation diagrams are also shown in Fig. 8.
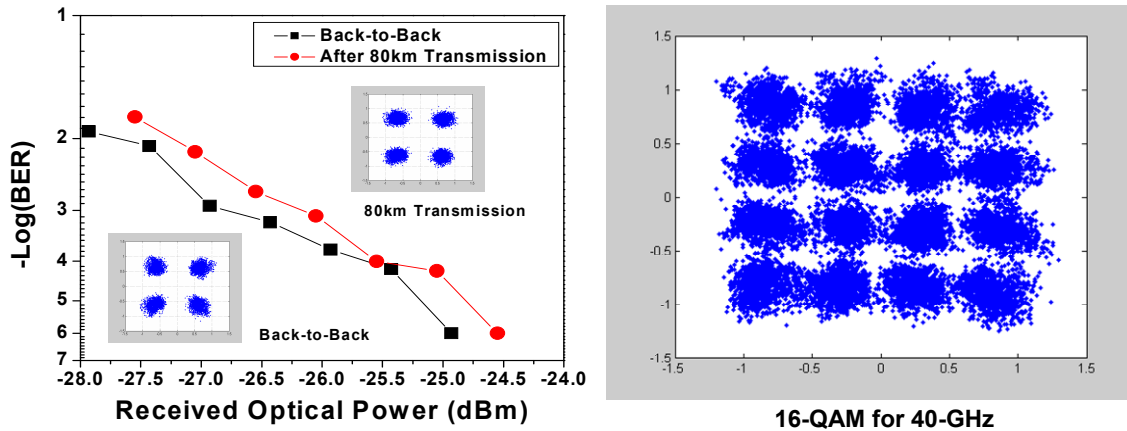

Fig. 8 Experimental results for OFDM optical-wireless systems.

3. CAMPUS-WIDE WIRELESS OVER OPTICAL FIBER FIELD TRAIL: DEMONSTRATION OF UNCOMPRESSED SD/HD VIDEO SERVICES

In this section, the first campus-wide uncompressed SD/HD video delivery is demonstrated through Georgia Tech campus fiber network, which is based on our developed technologies for optical millimeter-wave signal generation, transmission and processing in optical-wireless access systems. The field trial demonstration includes uncompressed SDTV and HDTV signals transmission over both 2.5-km standard single-mode fiber (SMF-28) and in-building air links.

The standards of HDTV and SDTV are both subsets of digital television systems. HDTV can provide high-quality video and audio entertainment than the SDTV which has different aspect ratios and formats in different parts of the world. For 4:3 aspect ratio in SDTV, the format containing 640 x 480 pixels is frequently used in those countries which follow the standard from National Television System Committee (NTSC), while the format of 720 x 576 pixels is used in the countries with Phase Alternating Line (PAL) standard. In comparison with SDTV, HDTV has much higher resolution. There are two common formats: 1280 x 720 pixels in progressive scan mode (abbreviated 720p) and 1920 x 1080 pixels in interlace mode or progress scan mode (abbreviated 1080i or 1080p). Both of them are using 16:9 aspect ratios. Society of Motion Picture and Television Engineers (SMPTE) 292M defines how the video, audio, and data are transmitted in a serial manner over coaxial cable normally at 1.485-Gb/s, which is usually refer to as high-definition serial digital interface (HD-SDI). Likewise, SMPTE 259M, which is called standard-definition serial digital interface (SD-SDI), is the standard for SDTV transmission over coaxial cables at lower data rate of 270-Mb/s [13].

Fig. 9 shows the system implementation of the first field demonstration of delivering dual service uncompressed 270-Mbps standard definition (SD) and uncompressed 1.485-Gbps full High definition (HD) video content using 2.4-GHz microwave and 60-GHz mm-wave radio signal over Georgia Tech Campus Fiber Backbone Network from Centergy building to Aware Home Residential Lab . The transmission distance is 2.5-km SMF-28. Fig. 10 shows the transmitter and receiver of at two locations. At the transmitter (Centergy), we used all-optical method to simultaneously generate 60-GHz mm-wave and up-convert 1.485-Gbps HD signal. For 2.4-GHz radio signal, we used electrical mixing and double-sideband optical modulation to upconvert 270-Mbps SD video content. At the receiver (Aware home), direct detection of optical 60-GHz mm-wave signal is performed by a 60-GHz bandwidth PIN photodiode to realize optical-to-

electrical conversion. The converted electrical mm-wave signal is then amplified by an electrical amplifier (EA) with 5GHz bandwidth centered at 60GHz and 3.55Vpp before it is broadcasted through a double-ridge guide rectangular horn antenna with a gain of 25dBi, frequency range of 50 to 75 GHz and 3 dB beam width of 7°. After the wireless transmission, the 60-GHz mm-wave signal is received by the end mobile terminal in order to perform the down-conversion and recover the 1.485-Gbps HD video signal. The down-conversion is performed by a 60-GHz balanced mixer using self-mixing technique. Similarly, the 2.4-GHz radio signal is received by a 2.5-GHz PIN receiver at the BS and distributed over the wireless to the receiver antenna. The 270-Mbps SD signal is then recovered by downconversion process.
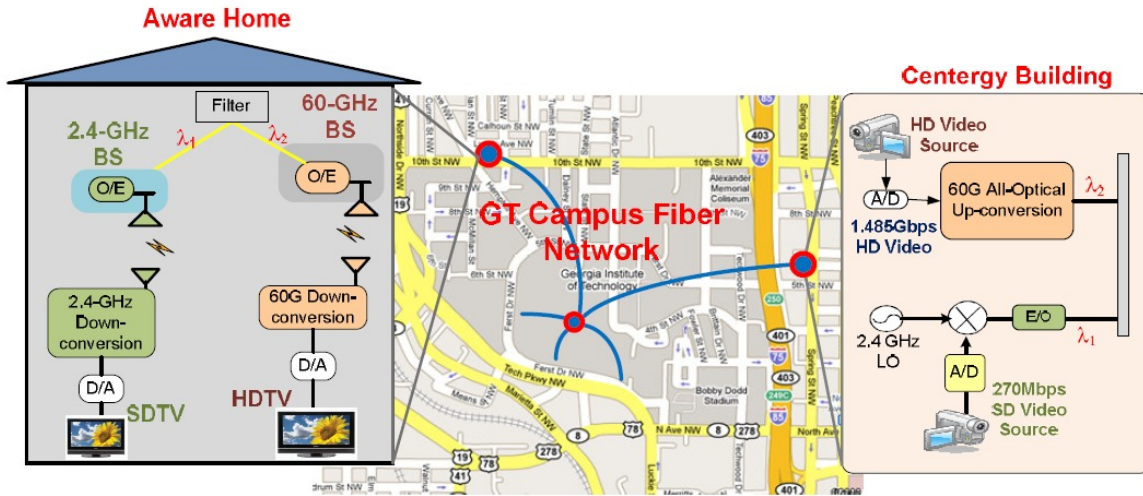

Fig. 9 Field deployment setup of the SD/HD video content delivery using 2.4-GHz and 60-GHz mm-wave radio over-Fiber in the Georgia Tech (GT) campus fiber network.

(a)   (b)
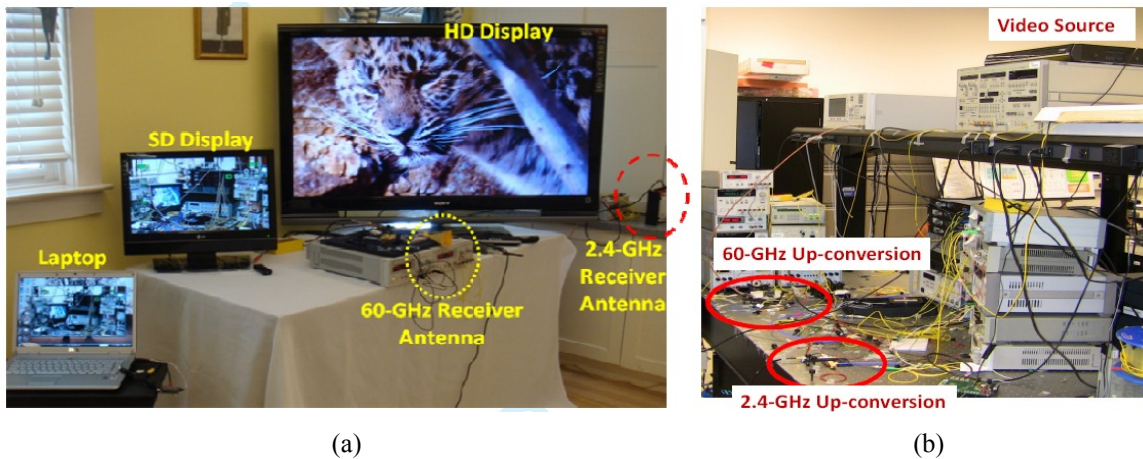
Fig. 10 Transmitter and receiver of the dual service 2.4-GHz and 60-GHz RoF carrying 270-Mbps SD and 1.485- Gbps HD video content (a) Receiver at Aware Home (b) Transmitter at Centergy Building.

4. CONCLUSIONS

The hybrid optical-wireless networks can explore the converged benefits of the optical and wireless technology to offer wireless HD services for both fixed and mobile end users. We have developed several key technologies for extending the transmission distance of optical millimeter-wave (40-60 GHz) signals by mitigating the fiber chromatic dispersion.

Based on PFT technology, 60-GHz optical millimeter-wave signals are successfully transmitted over 50-km SSMF without dispersion compensation. To our knowledge, this is the best result for 2.5-Gb/s on 60-GHz optical millimeter-wave in optical RF links. We also investigate the extended optical-wireless PON using remote optical upconversion at the LE and OFDM modulation format. We believe all the experimental results show that these technologies are highly practical to be deployed in the convergence of optical-wireless networks for wireless HD service delivery. Furthermore, using our developed technologies, a successful campus-wide field trial demonstration of radio-over-fiber (RoF) system is reported, which can deliver uncompressed SD and HD real-time video contents at 2.4-GHz and 60-GHz bands, respectively, over 2.5-km SMF-28 through the campus backbone network at Georgia Institute of Technology (GT).

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